Stellar Dynamics and Structure of Galaxies

Introduction. Spherically symmetric objects

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1. Introduction

2. Clusters
   - Globular Clusters
   - Open clusters
   - Clusters of galaxies
   - Comparison of hot stellar systems
Why study galaxies?

Cosmic Timeline

- The Universe was filled with ionized gas
- Hydrogen turned to be neutral
- The Cosmic Dark Age
  - First astronomical objects: formation of galaxies and quasars, beginning of the cosmic reionization
- Renaissance of the Universe - the End of the Dark Age
  - Completion of the reionization: inter-galactic medium was ionized
- Evolution of galaxies
- Formation of the solar system
- The Present Universe

Years after the Big Bang

- 0.3 million
- 0.5 billion
- 1 billion
- 2 billion (The epoch observed in the present research)
- 9 billion
- 13.5 billion

Images credit: NASA / WMAP Science Team, Solar System/MPC
Stellar Dynamics = Structure of Galaxies

NGC 634
Stellar Dynamics = Structure of Galaxies
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Orbits in axisymmetric potential. From Cappellari et al 2004
Stellar Dynamics = Structure of Galaxies

Observed light and velocity distribution is nothing but the superposition of stellar orbits
Why Study Galaxies?
Because they are beautiful!

- What is the mass distribution?
- On what orbits do stars, gas, dark matter, globular clusters move?
- How much mass contributed by each component?
- What can we learn about the formation and evolution?

With the hope to solve the following conundrums:

- Nature of the dark matter particle, interaction between dark matter and ordinary matter, formation of the first stars and galaxies, formation of the first black holes, black hole growth, jets, element abundance evolution
• Around solar radius, the typical distance between two stars is $10^{19}$ cm.
• What about the galaxy centre?
• Gas can shock. Gas can radiate.
• Cooling gas will lose energy, hence change the shape of the distribution.
Globular cluster properties

- Round, smooth distribution of stars (assume spherical)
- Population II (old) stars
- $10^4 - 10^6$ stars in each
- Ages $\sim 10^{10}$ years (from stellar evolution models and isochrone fitting).
- Traditionally measure surface brightness as a function of $R$ i.e. $\mu(R)$, or (more recently) use high resolution HST images to count stars $N(R)$. 
Galaxies Part II

Introduction
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Clusters of galaxies
Comparison of hot stellar systems

Top row: Messier 4 (ESO), Omega Centauri (ESO), Messier 80 (Hubble)
Middle row: Messier 53 (Hubble), NGC 6752 (Hubble), Messier 13 (Hubble)
Bottom row: Messier 4 (Hubble), NGC 288 (Hubble), 47 Tucanae (Hubble)
We want star mass density $\rho(r)$ as a function of radius:

- Use $M/L \sim 2$ solar units or star masses $M_*$ to convert $\mu(R)$ or $N(R)$ to surface mass density $\Sigma(R)$.
- Assume spherical symmetry $\Sigma(R) \rightarrow \rho(r)$
Globular cluster properties

Important radii

- At core radius $\mu(R_c) = \frac{1}{2}\mu(0)$, $R_c \sim 1.5$ pc. $\rho$ constant for $r < R_c$
- Median radius, typical radius, characteristic radius: contains half the light (2D). $R_h \sim 10$ pc.
- As we approach tidal radius: $\mu \to 0$, the “edge” of the cluster, is at $r_t \sim 50$ pc.
Globular cluster properties

Masses

- Total mass $M \lesssim 1 \times 10^4 M_\odot$
- Star masses up to 0.8 $M_\odot$
- Core density $\rho_c = \rho(0) \sim 8 \times 10^4 M_\odot$ pc$^{-3}$
- One-dimensional central velocity dispersion
  $$\sigma_r \equiv \sqrt{\langle v_r^2 \rangle} \sim 13 \text{ km s}^{-1}$$
  (ranges from 2 - 15 km s$^{-1}$)
Galaxies Part II

Open clusters

NGC 3603
Open cluster properties

- $N \sim 10^2 - 10^3$ stars
- Age $\lesssim 10^8$ years $\Rightarrow$ either all formed recently or form and disperse continually.
- $R_c \sim 1$ pc
- $R_h \sim 2$ pc
- $r_t \sim 10$ pc, because of stronger gravity in the disk of the Galaxy, and lower cluster mass.
- Mass $\sim 250$ M$_\odot$
- $M/L \sim 1$ (solar units)
- $\rho_c \sim 100$ M$_\odot$ pc$^{-3}$ (cf solar neighbourhood $\bar{\rho} = 0.05$ M$_\odot$ pc$^{-3}$).
- $\sigma_r = \sqrt{\bar{v}_r^2} \sim 1$ km s$^{-1}$ (system assumed approximately isothermal).
Galaxies Part II

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Clusters

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Galaxy clusters

Abell 1689
Properties of galaxy clusters

- Large range of $N$, and wide spread of $M$, but typically $N \sim 100$ galaxies, and total masses $\sim 10^{15} \, M_\odot$ (much of the mass is not visible).
- $R_c \sim 250 \, \text{kpc}$
- $R_h \sim 3 \, \text{Mpc}$
- $\sigma_r \sim 800 \, \text{km s}^{-1}$
- Crossing time

$$t_{\text{cross}} \sim \frac{R_h}{\sigma_r} \sim 10^9 \left( \frac{R_h}{1 \, \text{Mpc}} \right) \left( \frac{\sigma_r}{10^3 \, \text{km s}^{-1}} \right)^{-1}$$

- Age $\lesssim 13.7 \times 10^9 \, \text{yr}$ (age of the universe) $\Rightarrow$ dynamically young, often still forming, collapsing for the first time.
Comparison of hot stellar systems
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